QCD Spin Physics

(some aspects)

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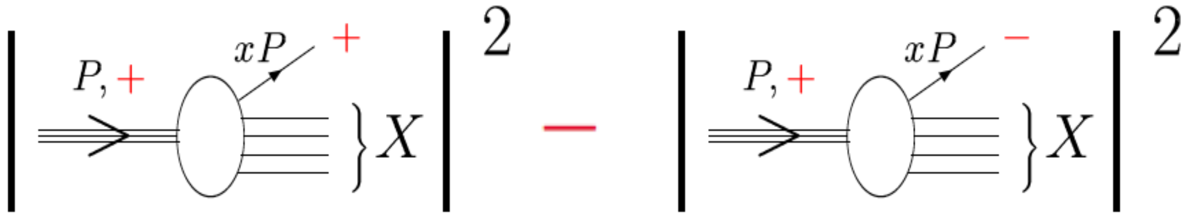
Outline:

- Nucleon helicity structure
  - global analysis of parton distributions
  - W physics at RHIC
- Drell-Yan (spin) physics
  - soft-gluon resummation
  - valence structure of the pion
- Conclusions

Nucleon Helicity Structure

Helicity Parton Distributions:

$\Delta q(x) =$



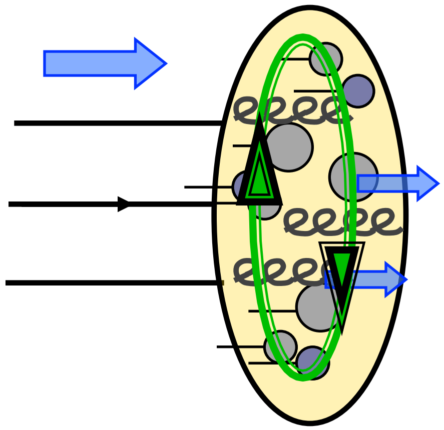
$\Delta g(x) =$

$$\Delta q(x) = \frac{1}{4\pi} \int dy^- \, e^{-iy^- xP^+} \langle P, S \,|\, \bar{\psi}(0, y^-, \mathbf{0}_\perp) \, \gamma^+ \gamma_5 \, \psi(0) \,|\, P, S \rangle$$

$$\Delta g(x) = \frac{1}{4\pi x P^+} \int dy^- \, e^{-iy^- xP^+} \langle P, S \,|\, F^{+\alpha}(0, y^-, \mathbf{0}_\perp) \, \tilde{F}_\alpha^{\ +}(0) \,|\, P, S \rangle$$

Collins, Soper; Manohar

(1) Δq, Δg and the proton spin



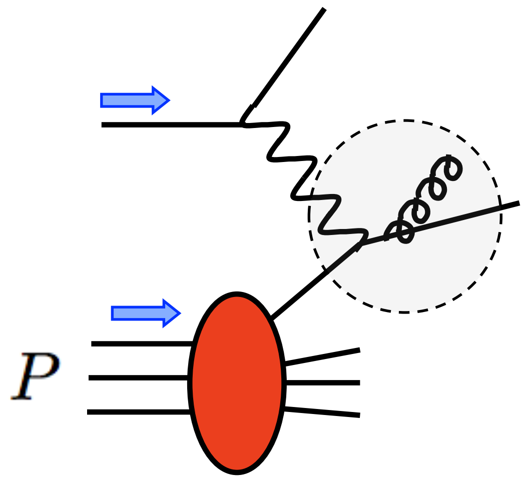
Jaffe, Manohar; Jaffe, Bashinsky;
Brodsky; Chen et al.; Wakamatsu

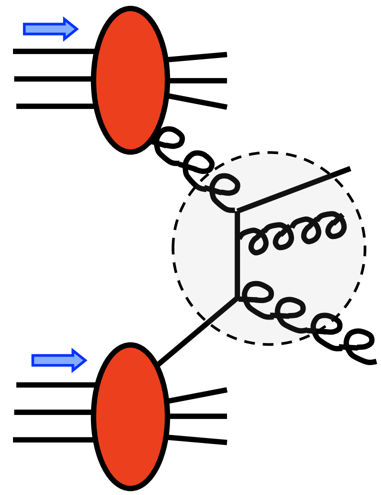
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g$$

$$\Delta\Sigma = \int_0^1 dx \left[\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}\right](x)$$

$$\Delta G = \int_0^1 dx\, \Delta g(x)$$

(2) Δq, Δg and short-distance QCD





$$\Delta\sigma = \sum_{f=q,\bar{q},g} \int dx\, \Delta f(x,Q^2)\, \Delta\hat{\sigma}^f(xP, \alpha_s(Q^2)) + \ldots$$

$$\Delta\sigma = \sum_{a,b=q,\bar{q},g} \int dx_a\, \Delta f_a(x_a, p_\perp^2) \int dx_b\, \Delta f_b(x_b, p_\perp^2) \Delta\hat{\sigma}^{ab}(x_a P, x_b P', \alpha_s(p_\perp^2)) + \ldots$$

$$\Delta\hat{\sigma} = \Delta\hat{\sigma}_{\mathrm{LO}} + \alpha_s \Delta\hat{\sigma}_{\mathrm{NLO}} + \ldots$$

- Many higher-order calculations for polarized hard-scattering (both ep, pp)

- DGLAP evolution:

$$\mu^2 \frac{\mathrm{d}}{\mathrm{d}\mu^2} \begin{pmatrix} \Delta q(x,\mu^2) \\ \Delta g(x,\mu^2) \end{pmatrix} = \int_x^1 \frac{dz}{z} \begin{pmatrix} \Delta\mathcal{P}_{qq} & \Delta\mathcal{P}_{qg} \\ \Delta\mathcal{P}_{gq} & \Delta\mathcal{P}_{gg} \end{pmatrix} \begin{pmatrix} \Delta q \\ \Delta g \end{pmatrix} \left(\frac{x}{z},\mu^2\right)$$

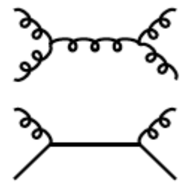
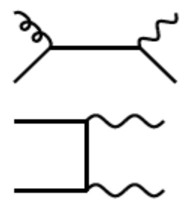
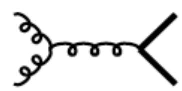
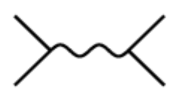
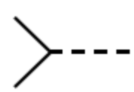
$$\Delta\mathcal{P}_{ij} = \frac{\alpha_s}{2\pi}\Delta\mathcal{P}_{ij}^{\mathrm{LO}} + \left(\frac{\alpha_s}{2\pi}\right)^2 \Delta\mathcal{P}_{ij}^{\mathrm{NLO}} + \left(\frac{\alpha_s}{2\pi}\right)^3 \Delta\mathcal{P}_{ij}^{\mathrm{NNLO}} + \ldots$$

↑ Ahmed, Ross
Altarelli, Parisi, ...
1977

↑ Mertig, van Neerven
WV 1995

↑ Moch, Rogal, Vogt, Vermaseren 2008
(ij = qq, qg)

Polarized pp scattering (RHIC) :

Reaction	Dom. partonic process	probes	LO Feynman diagram
$\vec p \vec p \to \pi + X$	$\vec g \vec g \to gg$ $\vec q \vec g \to qg$	Δg	
$\vec p \vec p \to \text{jet(s)} + X$	$\vec g \vec g \to gg$ $\vec q \vec g \to qg$	Δg	(as above)
$\vec p \vec p \to \gamma + X$ $\vec p \vec p \to \gamma + \text{jet} + X$ $\vec p \vec p \to \gamma\gamma + X$	$\vec q \vec g \to \gamma q$ $\vec q \vec g \to \gamma q$ $\vec q \vec{\bar q} \to \gamma\gamma$	Δg Δg $\Delta q, \Delta \bar q$	
$\vec p \vec p \to DX, BX$	$\vec g \vec g \to c\bar c, b\bar b$	Δg	
$\vec p \vec p \to \mu^+\mu^- X$ (Drell-Yan)	$\vec q \vec{\bar q} \to \gamma^* \to \mu^+\mu^-$	$\Delta q, \Delta \bar q$	
$\vec p \vec p \to (Z^0, W^\pm) X$ $p \vec p \to (Z^0, W^\pm) X$	$\vec q \vec{\bar q} \to Z^0$, $\vec q\,' \vec{\bar q} \to W^\pm$ $\vec q\,' \bar q \to W^\pm$, $q' \vec{\bar q} \to W^\pm$	$\Delta q, \Delta \bar q$	

NLO:

Jäger, Schäfer, Stratmann, WV

Jäger, Stratmann, WV; Signer et al.

Gordon, WV; Contogouris et al.; Gordon, Coriano; Frixione. WV

Stratmann, Bojak

Weber; Gehrmann; Kamal; Smith, van Neerven, Ravindran; Nadolsky, Yuan; de Florian, WV

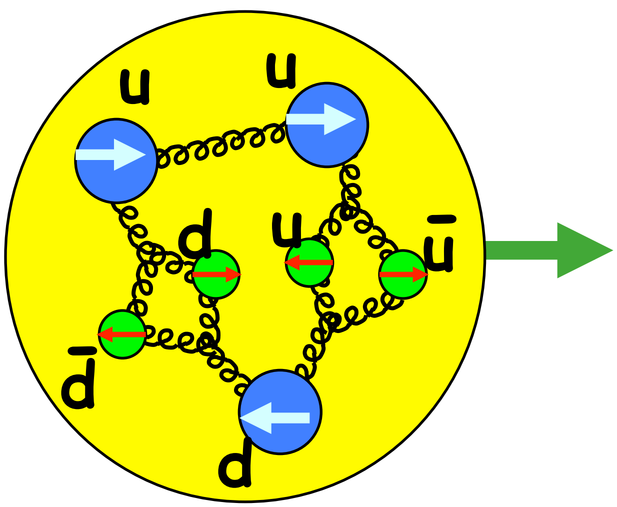
(3) Δq, Δg "beyond proton spin sum rule"

Lattice, Models of nucleon structure

- valence region, e.g. $$\frac{\Delta d}{d} \xrightarrow{x \to 1} \begin{cases} 1 & \text{counting rules/pQCD} \\ -1/3 & \text{const. quark model} \end{cases}$$

- flavor / sea structure, e.g. $\Delta\bar{u}$ vs. $\Delta\bar{d}$

qualitatively:



large-N_c,
chiral quark models,
meson cloud,...

- connection to hyperon β decays, SU(3)

$$\Delta\Sigma_q \equiv \int_0^1 dx\,(\Delta q + \Delta\bar{q})\,(x, Q^2) \;\; \propto \; \langle\, P, s\,|\,\bar{\psi}_q\,\gamma^\mu\gamma_5\,\psi_q\,|\,P, s\,\rangle$$

(axial charges)

Bjorken;
Ellis, Jaffe;
Sehgal;
Karliner, Lipkin;
Ratcliffe;...

$$\Delta\Sigma_u - \Delta\Sigma_d \;=\; g_A = 1.257 \pm \ldots$$

$$\Delta\Sigma_u + \Delta\Sigma_d - 2\Delta\Sigma_s \;=\; 3F - D \;=\; 0.58 \pm 0.03$$

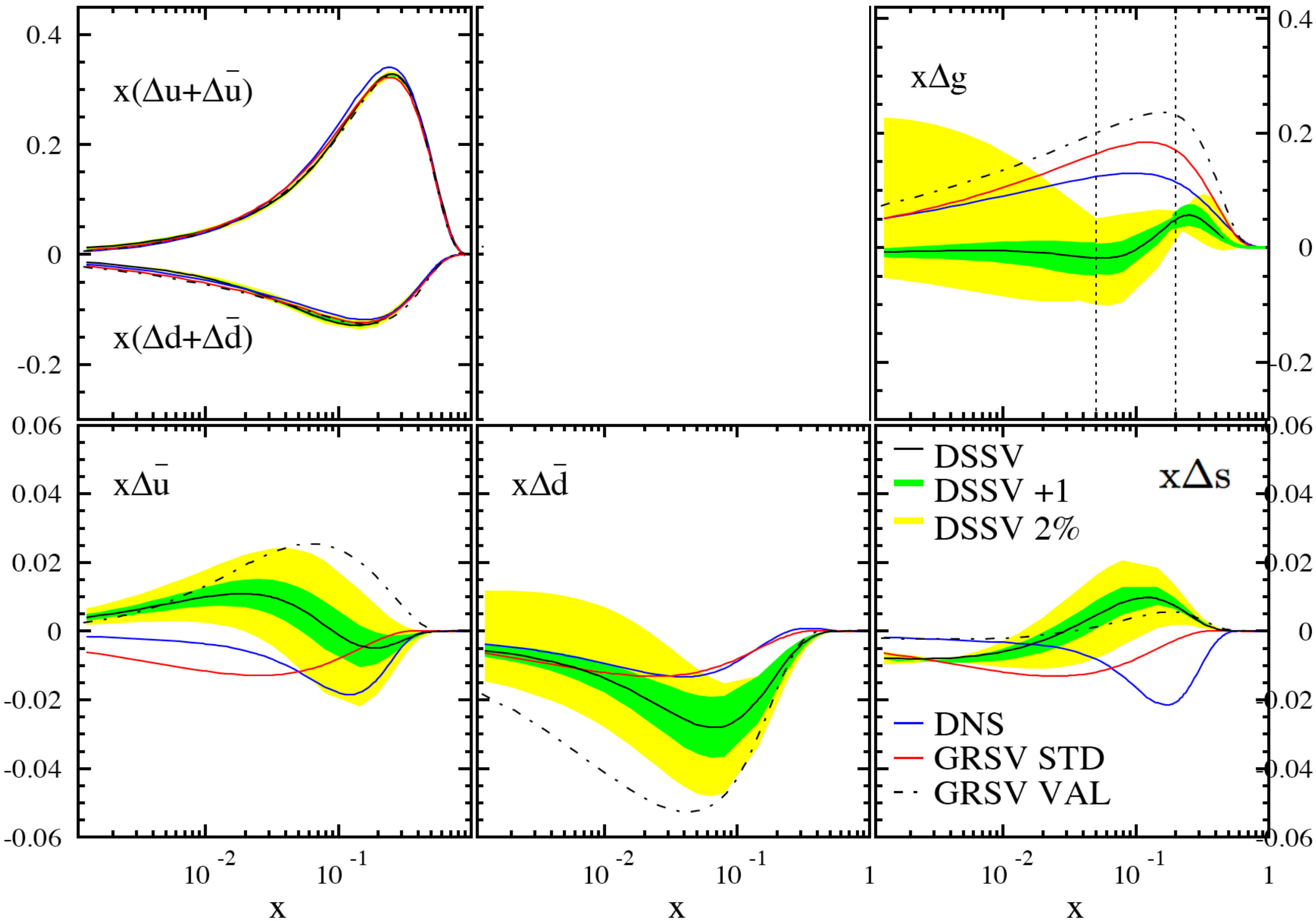
?

- strangeness

$$\Delta\Sigma \;=\; \Delta\Sigma_u + \Delta\Sigma_d + \Delta\Sigma_s = \; 3F - D \,+\, 3\Delta\Sigma_s$$

$\Delta q, \Delta g$: Status

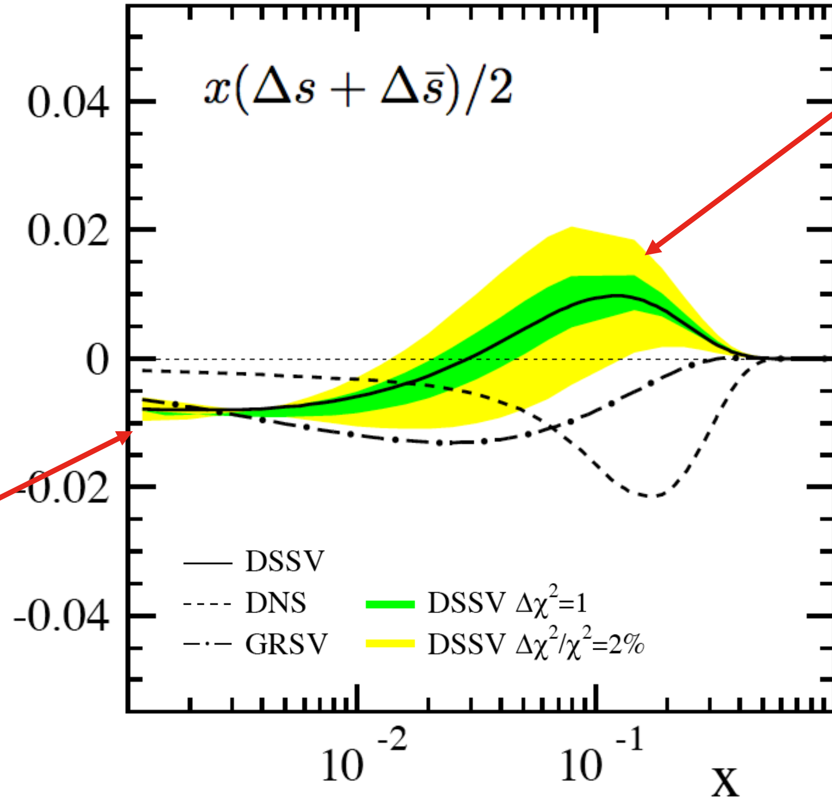
DSSV: global analysis of DIS, SIDIS, RHIC data



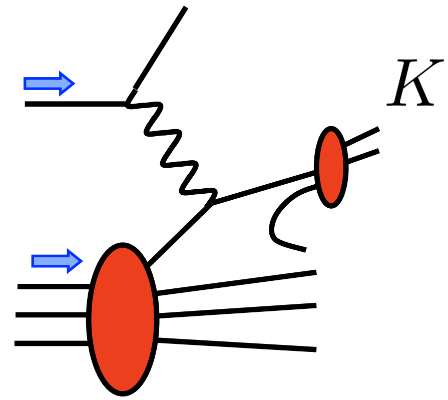
$Q^2 = 10 \text{ GeV}^2$

de Florian, Sassot, Stratmann, WV

- strangeness :



SIDIS



driven by SU(3) (3F-D)

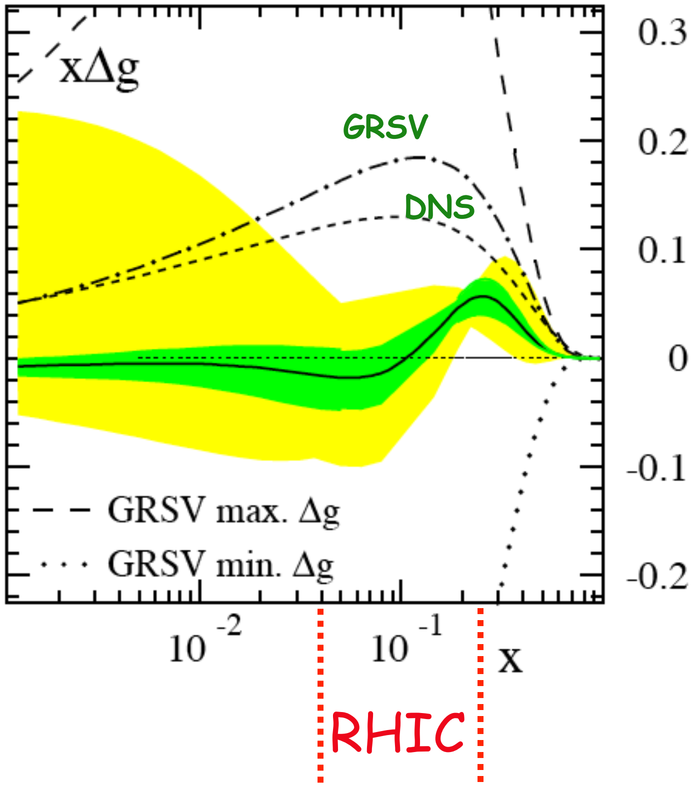
$$\int_{0.001}^{1} dx\, \Delta s(x) \;=\; -0.006 \pm 0.01 \qquad (\Delta\chi^2 = 1)$$

?

$$\int_{0}^{1} dx\, \Delta s(x) \;=\; -0.057 \pm ?$$

using F,D and SU(3)

$$\int_{0.001}^{1} dx \Delta\Sigma \;=\; 0.366 \pm 0.016 \qquad \int_{0}^{1} dx \Delta\Sigma \;=\; 0.242 \pm ?$$

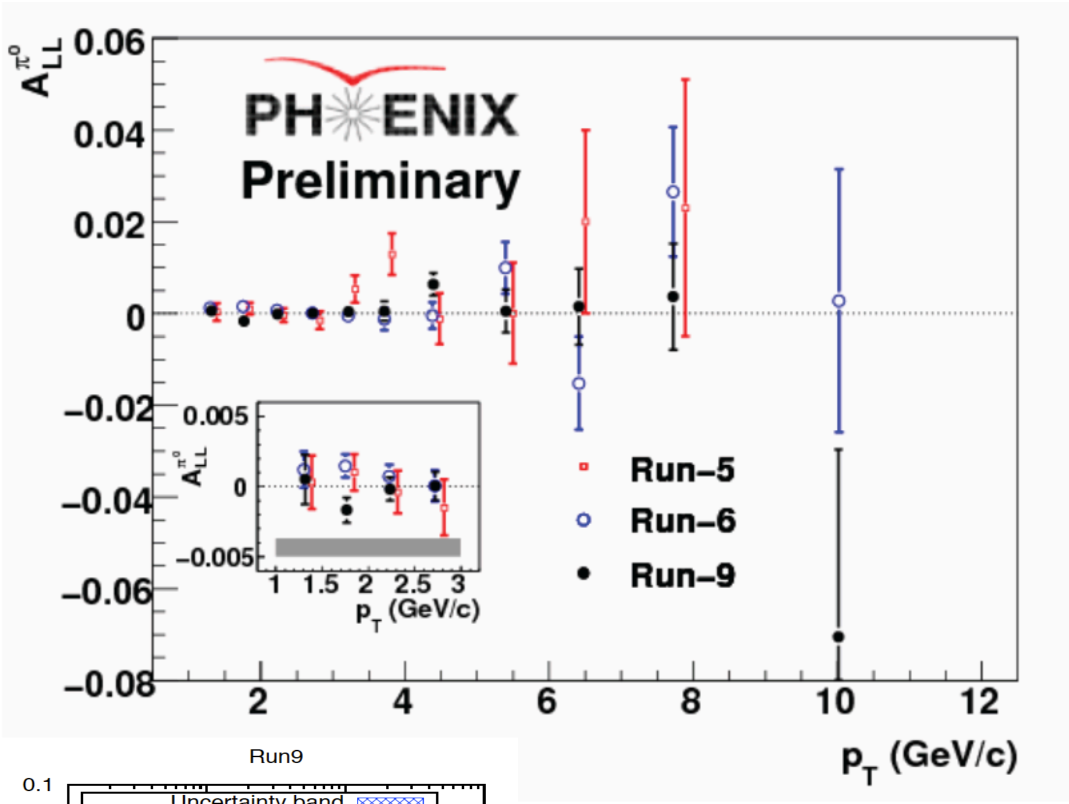


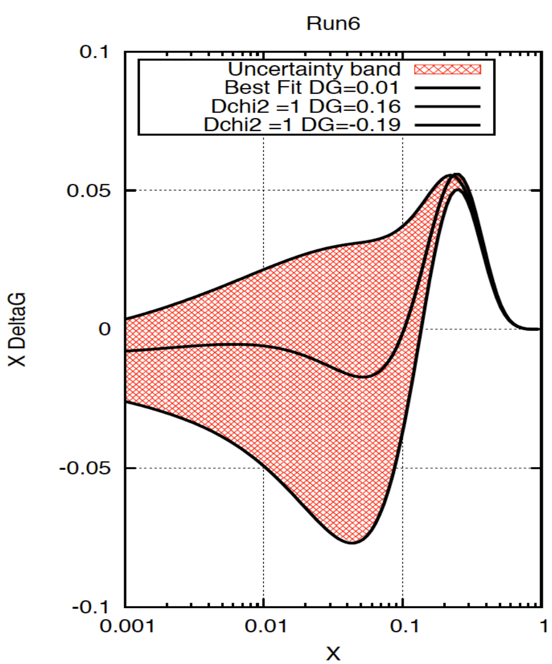
$$\int_{0.05}^{0.2} dx\, \Delta g \;=\; 0.006 \pm 0.06 \qquad (\Delta\chi^2 = 1)$$

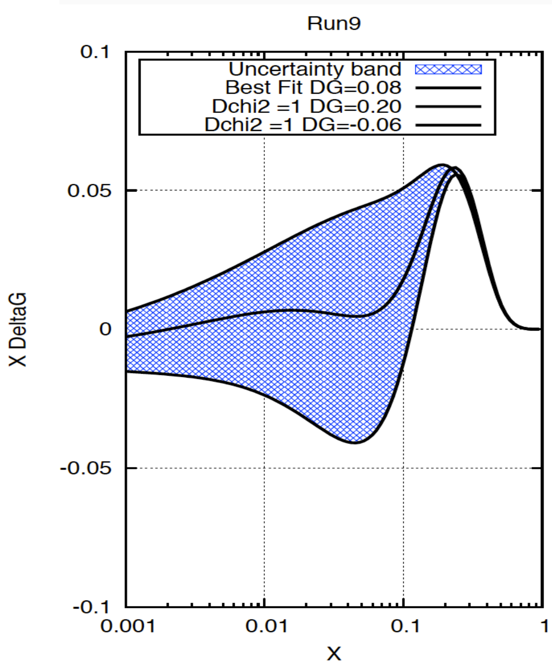
$$\int_{0}^{1} dx\, \Delta g \;=\; -0.084 \pm ?$$

- there could still be significant contribution to proton spin

Constraints become better with new data:

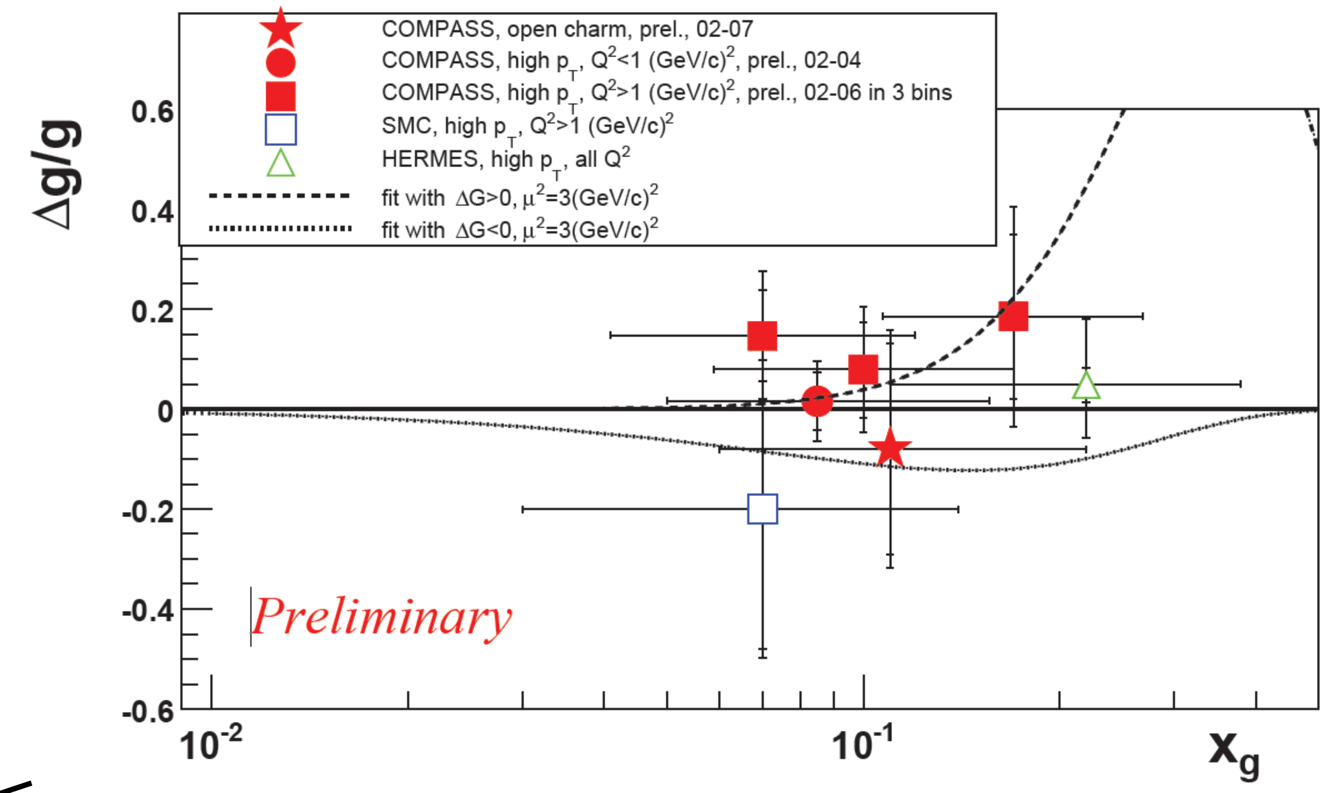


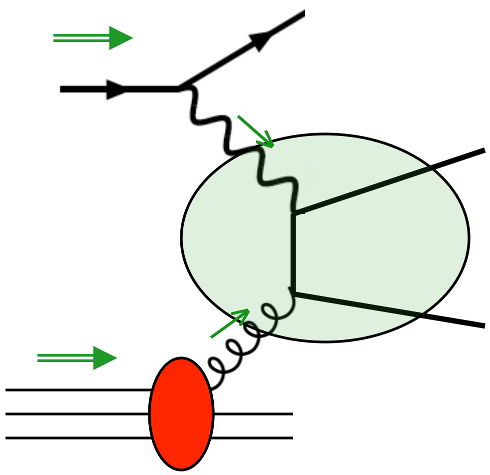




S.Taneja

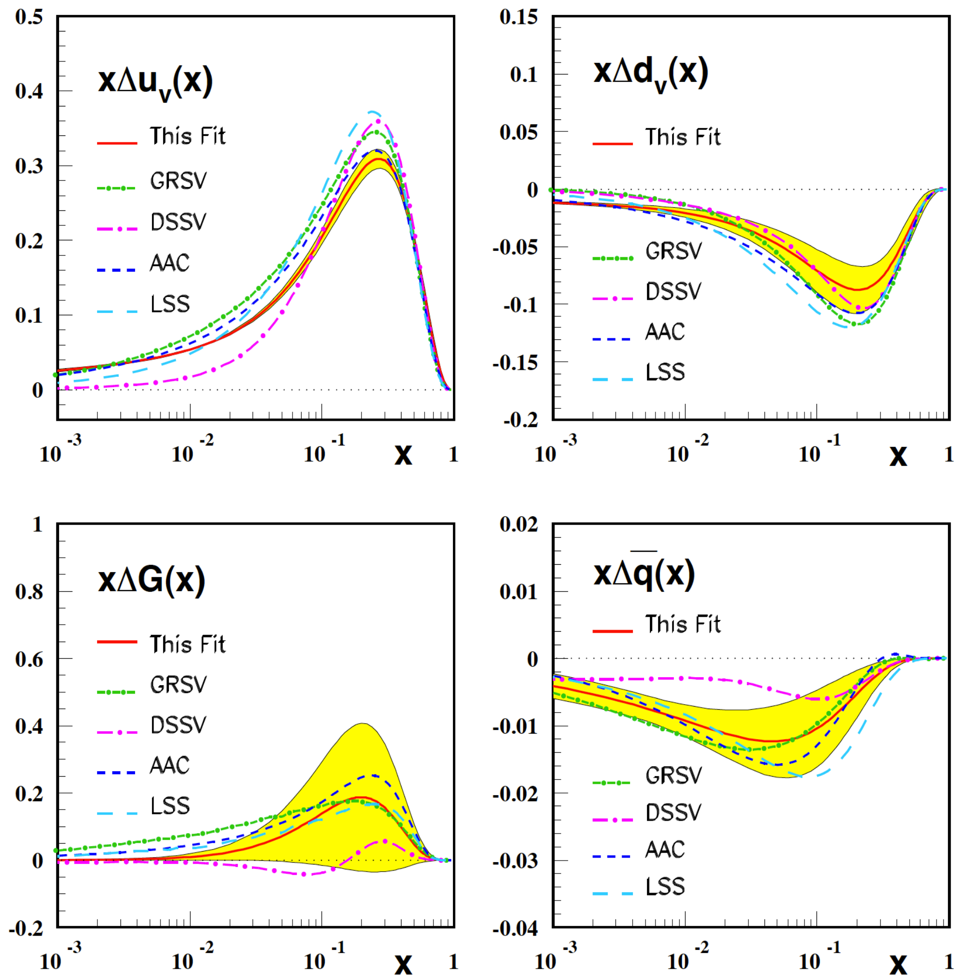
Most recent COMPASS data:





- other analyses of polarized-DIS data (incl. new data):

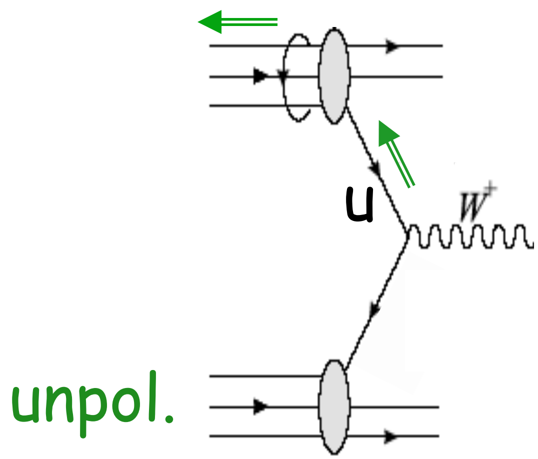
Blümlein, Böttcher; Leader, Stamenov, Sidorov; Forte et al. (NNPDFs)



Blümlein, Böttcher

Focus on target-mass corrections, higher-twist, α_s

The latest: W-boson production at RHIC



$$\sqrt{s} = 500 \text{ GeV}$$

- **large Parity Violation effect** $$A_L = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \neq 0$$
- **complementary to SIDIS, but cleaner**
- **new NLO for polarized case:** **de Florian, WV**
  tailored for inclusion in global analysis

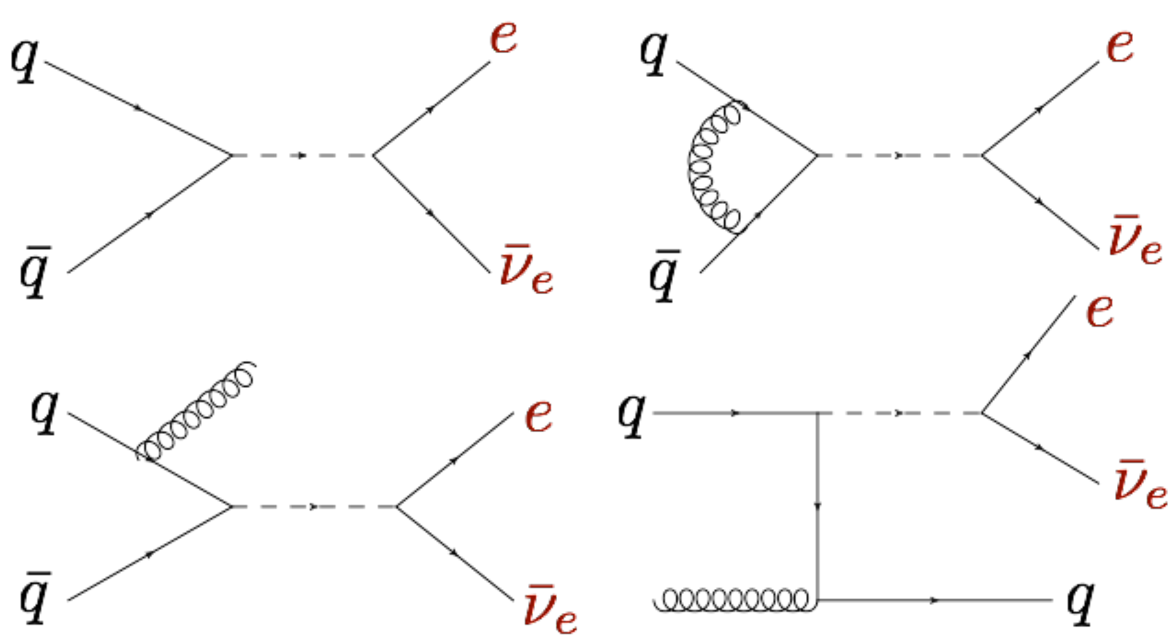
New channels at NLO

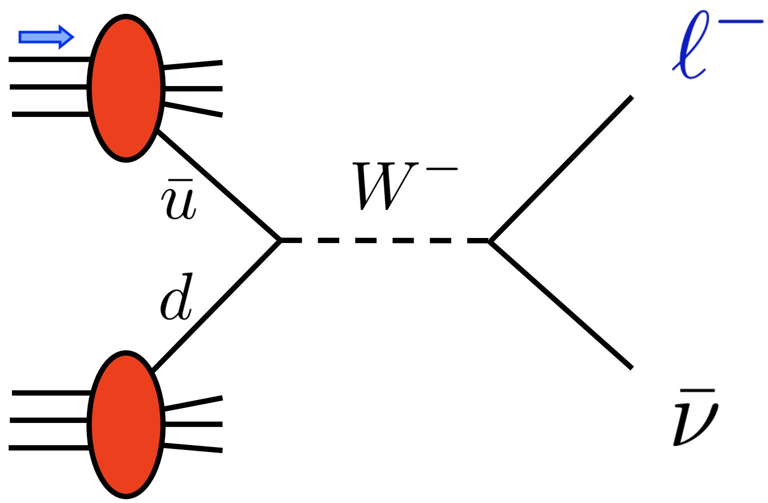
$$\begin{aligned}
\Delta\bar{q}\; q &\rightarrow e\,\bar{\nu}_e \\
\Delta q\; \bar{q} &\rightarrow e\,\bar{\nu}_e \\
\Delta\bar{q}\; g &\rightarrow e\,\bar{\nu}_e\,\bar{q} \\
\Delta g\; \bar{q} &\rightarrow e\,\bar{\nu}_e\,\bar{q} \\
\Delta q\; g &\rightarrow e\,\bar{\nu}_e\,g \\
\Delta g\; q &\rightarrow e\,\bar{\nu}_e\,g
\end{aligned}$$

Subtraction Method

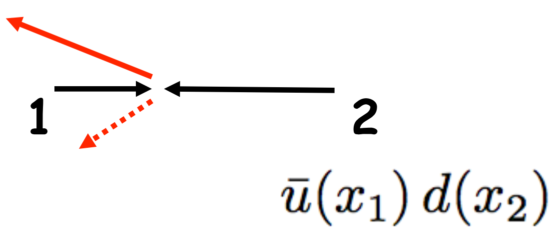
Ellis, Kunszt, Soper; ...

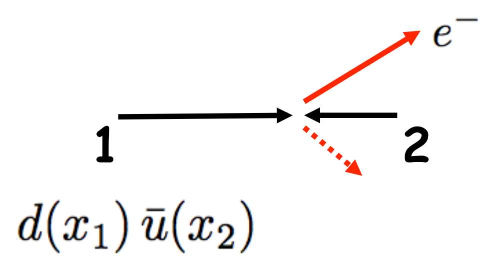
Some diagrams



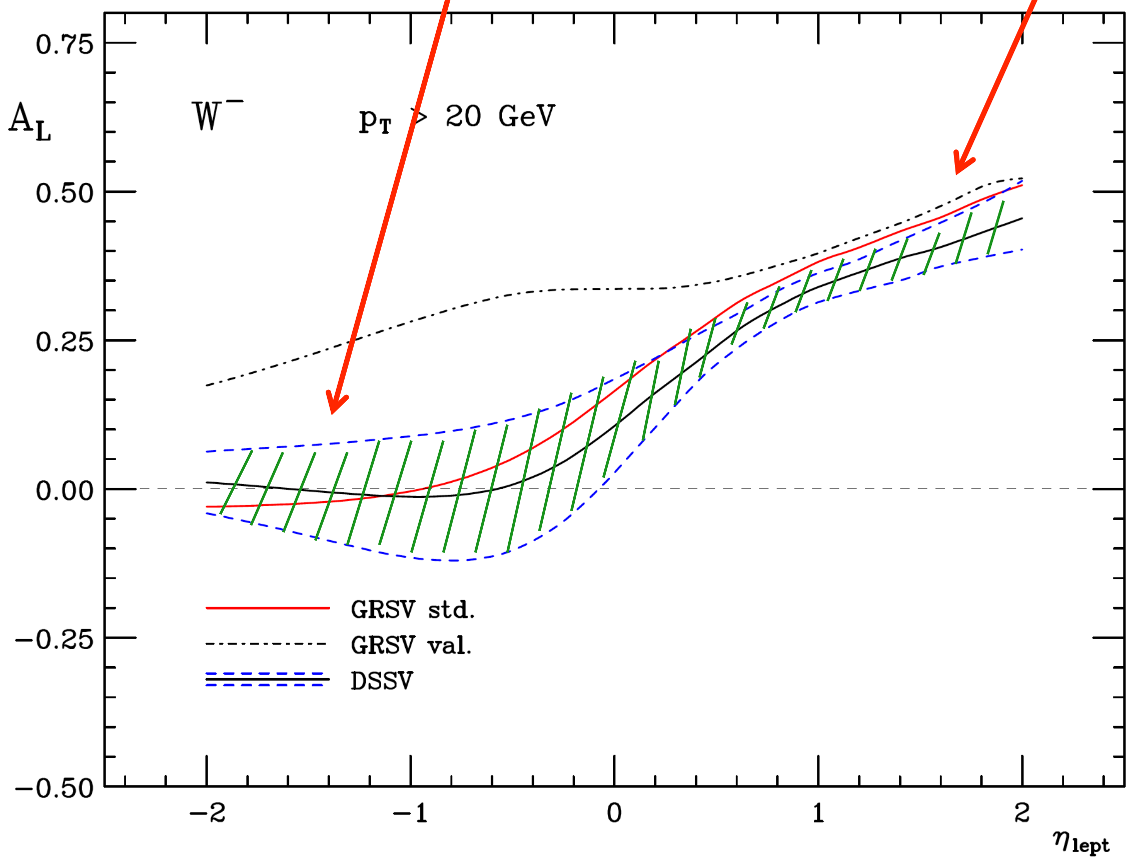


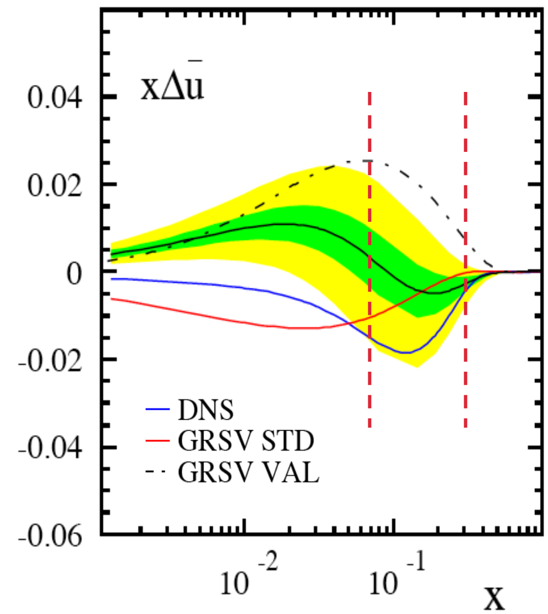
$$\sigma^{W^-} \propto \bar{u}(x_1)\, d(x_2)\, (1-\cos\theta)^2 + d(x_1)\, \bar{u}(x_2)\, (1+\cos\theta)^2$$



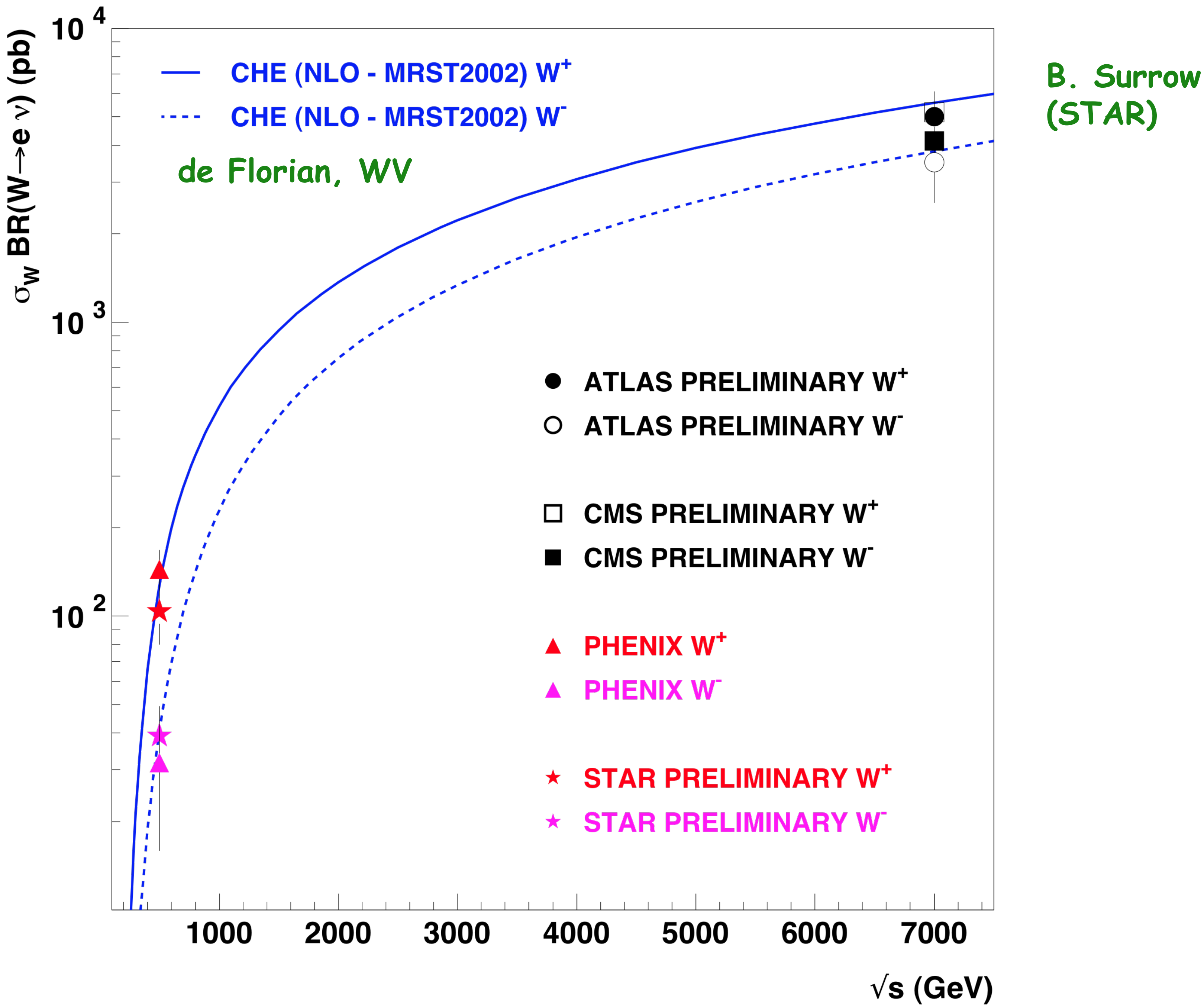


$$A_L^{e^-} \approx \frac{\int_{\otimes(x_1,x_2)} [\Delta\bar{u}(x_1) d(x_2)(1-\cos\theta)^2 - \Delta d(x_1)\bar{u}(x_2)(1+\cos\theta)^2]}{\int_{\otimes(x_1,x_2)} [\bar{u}(x_1) d(x_2)(1-\cos\theta)^2 + d(x_1)\bar{u}(x_2)(1+\cos\theta)^2]}$$



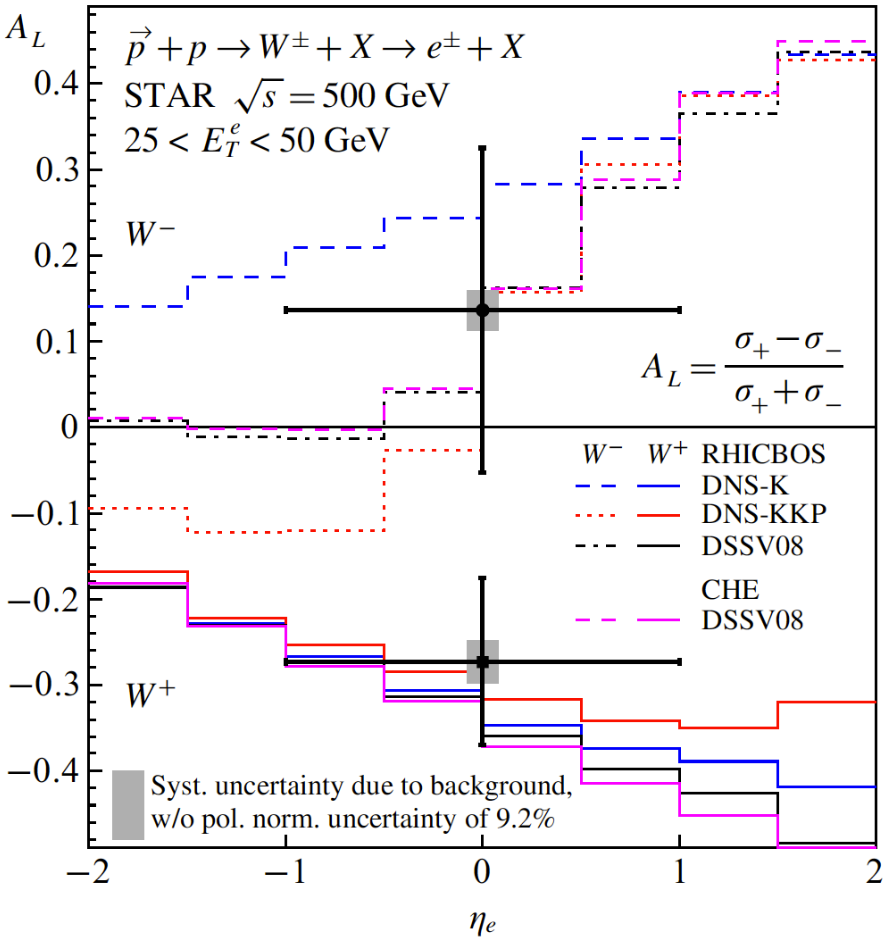


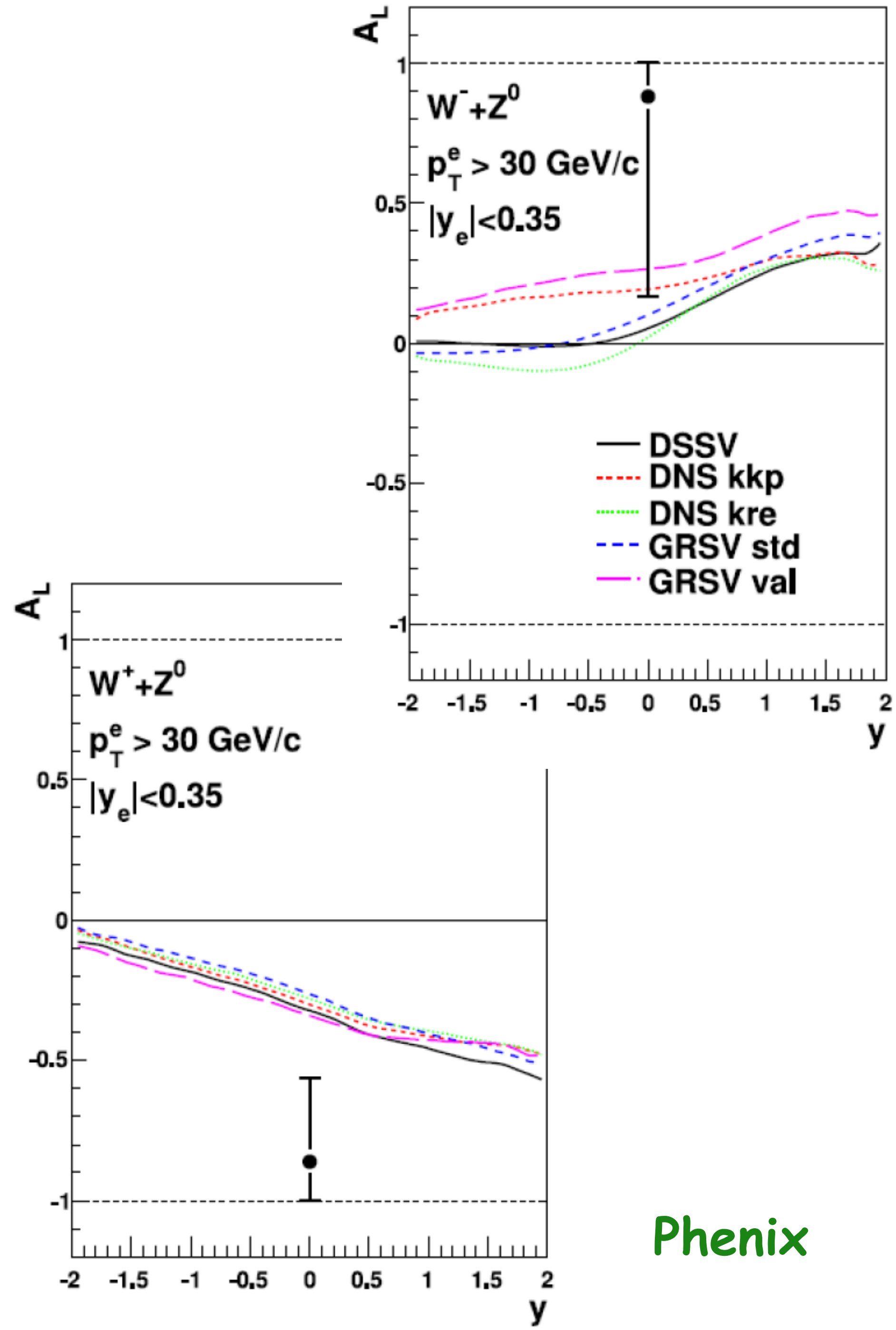
$\theta > \frac{\pi}{2}$ $\theta < \frac{\pi}{2}$



B. Surrow
(STAR)
CHE (NLO - MRST2002) W+
CHE (NLO - MRST2002) W-
de Florian, WV
ATLAS PRELIMINARY W+
ATLAS PRELIMINARY W-
CMS PRELIMINARY W+
CMS PRELIMINARY W-
PHENIX W+
PHENIX W-
STAR PRELIMINARY W+
STAR PRELIMINARY W-
σW BR(W→e ν) (pb)
√s (GeV)

STAR


$\vec{p} + p \rightarrow W^{\pm} + X \rightarrow e^{\pm} + X$
STAR $\sqrt{s} = 500$ GeV
$25 < E_T^e < 50$ GeV
A_L
W^-
W^+
$A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$
W^- W^+ RHICBOS
DNS-K
DNS-KKP
DSSV08
CHE
DSSV08
Syst. uncertainty due to background,
w/o pol. norm. uncertainty of 9.2%
η_e


A_L
$W^- + Z^0$
$p_T^e > 30$ GeV/c
$|y_e| < 0.35$
DSSV
DNS kkp
DNS kre
GRSV std
GRSV val
y
A_L
$W^+ + Z^0$
$p_T^e > 30$ GeV/c
$|y_e| < 0.35$
y

Phenix

Drell-Yan spin physics

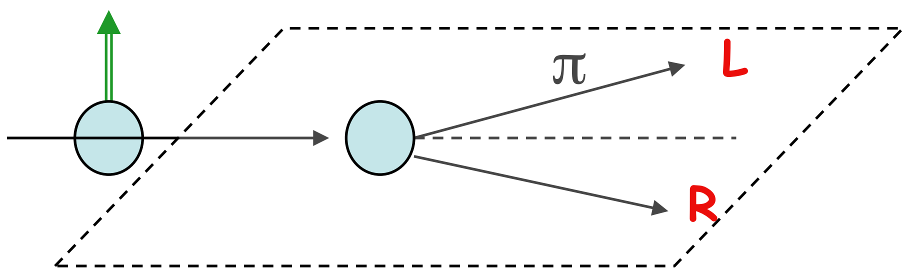
Drell-Yan presently is key focus in spin physics:

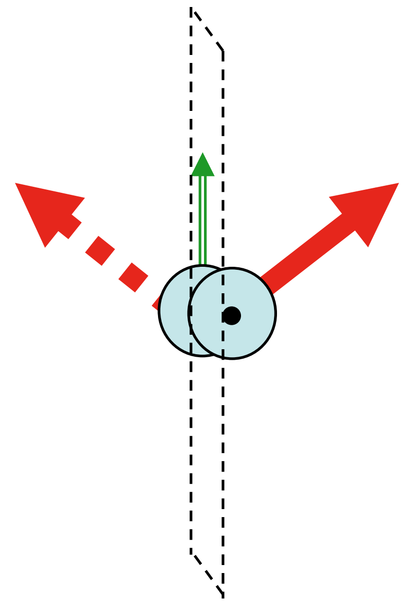
- important spin phenomena
- in pp, pN: probe of anti-quark distributions, high-x
- in πN: probe of pion structure
- LO is color-singlet annihilation $q\bar{q} \rightarrow \gamma^*$
  - higher-orders under control

Currently: E906 ongoing

RHIC, COMPASS near-term plans

J-PARC, FAIR future possibilities





$$A_N = \frac{L-R}{L+R}$$

"Single-spin asymmetry"

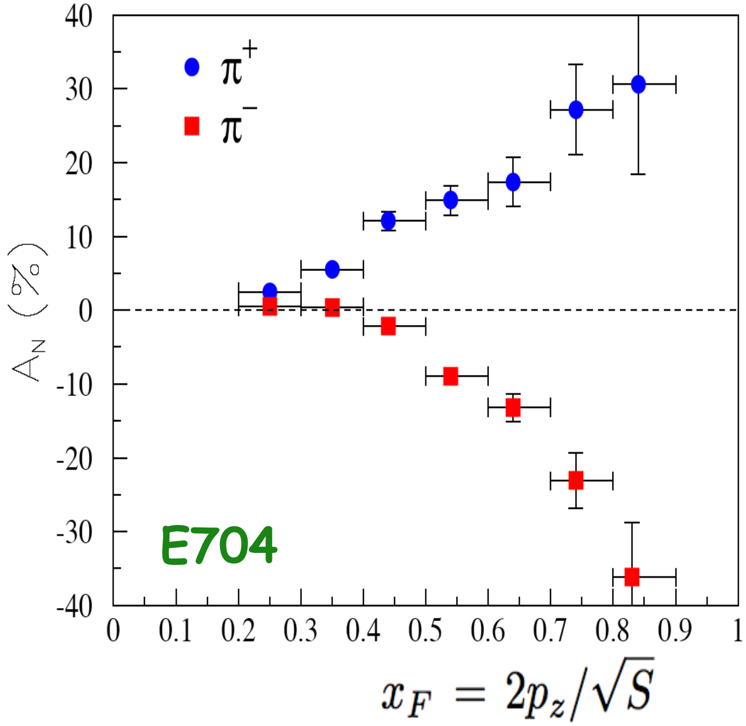
$$\vec{S}_\perp \cdot \left(\vec{P} \times \vec{p}_\perp^{\,\pi}\right)$$

$$A_N \sim \mathcal{I}m(\, M_+ \, M_-^* \,)$$

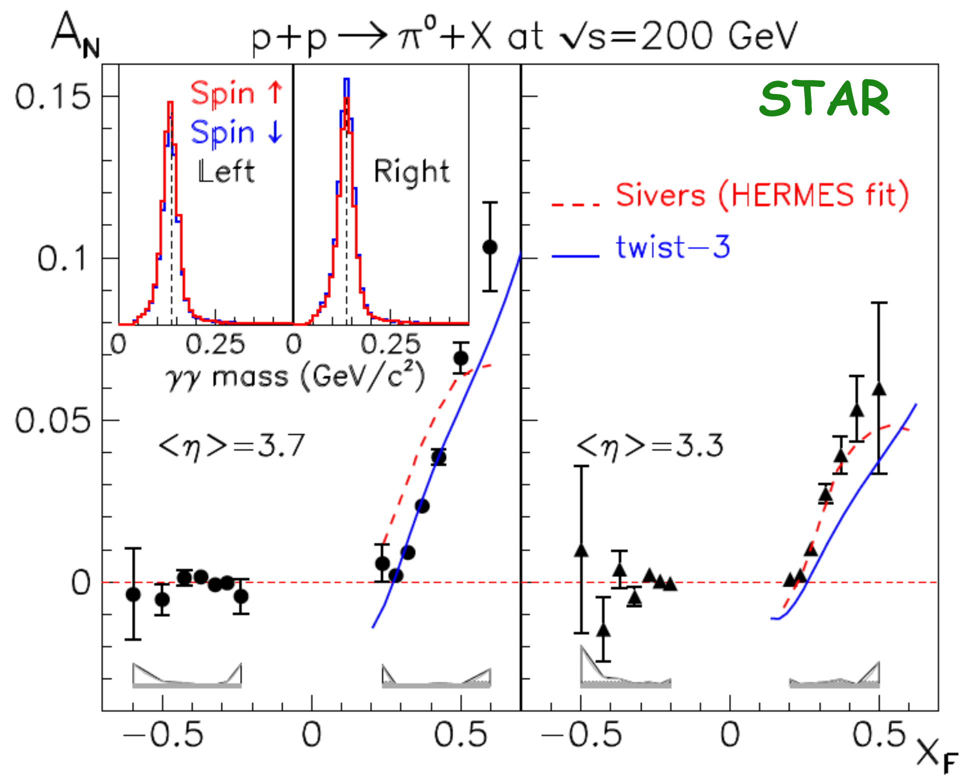
- expect $A_N \sim \frac{m_q}{p_\perp} \alpha_s \ll 1$ in simple parton model

Kane, Pumplin, Repko '78

Instead:



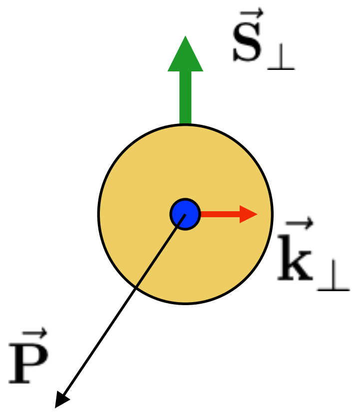
40
30
20
10
0
-10
-20
-30
-40
A_N (%)
π^+
π^-
E704
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
$x_F = 2p_z/\sqrt{S}$



A_N
$p+p \rightarrow \pi^0+X$ at $\sqrt{s}$=200 GeV
STAR
Spin ↑
Spin ↓
Left
Right
0 0.25 0 0.25
$\gamma\gamma$ mass (GeV/c^2)
Sivers (HERMES fit)
twist−3
<η>=3.7
<η>=3.3
0.15
0.1
0.05
0
−0.5 0 0.5 −0.5 0 0.5
X_F

- Do observed asymmetries arise directly from asymmetries at quark level ?

Sivers '90



$$[\mathbf{S}_\perp \cdot (\hat{\mathbf{P}} \times \mathbf{k}_\perp)]\ f_q^{\rm Sivers}(x, k_\perp)$$

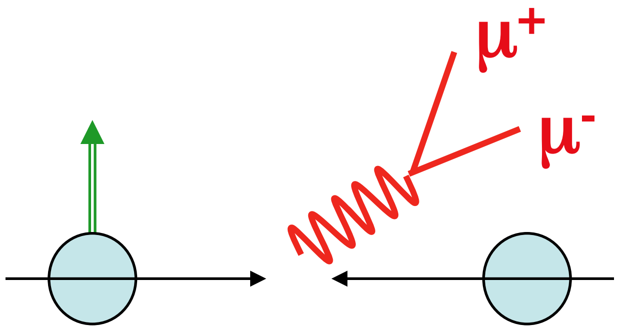
"Sivers function"

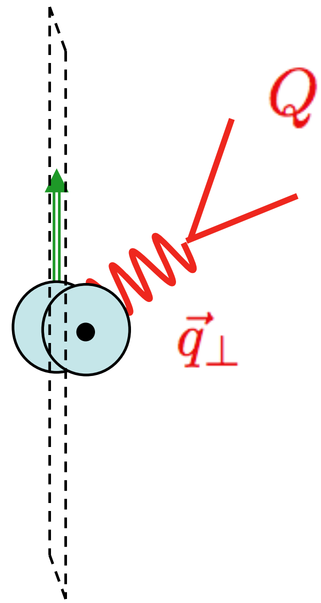
Phenomenology: **Anselmino, Boglione, D'Alesio, Leader, Melis, Murgia, ...**

- $pp \to \pi X$: complicated theoretically

Where could one see Sivers correlation in a direct way ?

Example I: Drell-Yan





$$A_N = \frac{L-R}{L+R}$$

For $q_\perp \ll Q$ have factorization in *transv. momentum*:

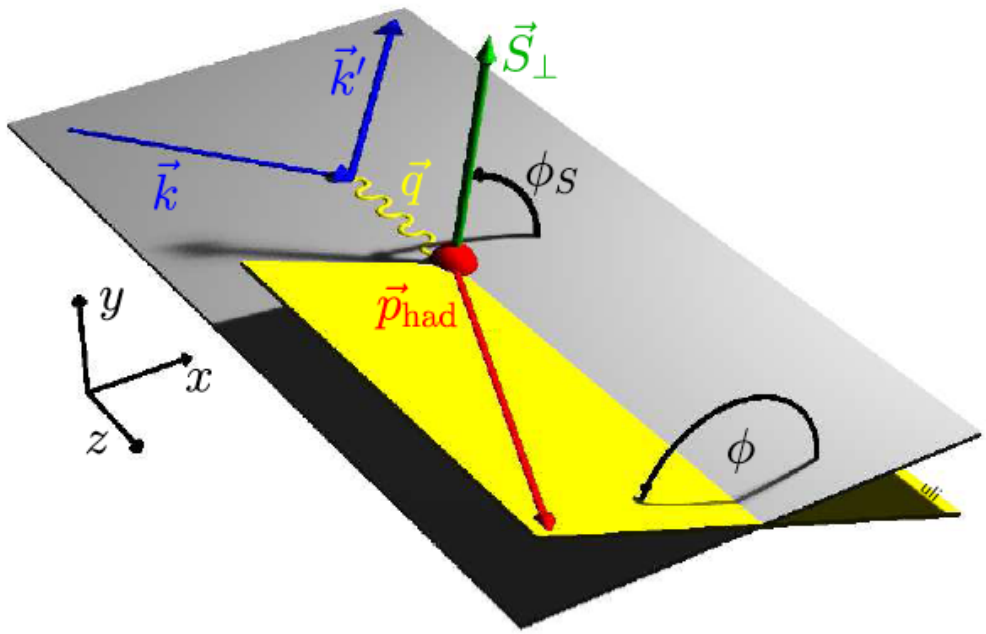
Ji, Ma, Yuan

Hard part

$$\frac{d\sigma^\uparrow}{d^2q_\perp} - \frac{d\sigma^\downarrow}{d^2q_\perp} \sim \sum_f H(Q^2) \int d^2k_{\perp,1} \int d^2k_{\perp,2}$$

$$\times \left[\vec{S}_\perp \cdot \left(\hat{\vec{P}} \times \hat{\vec{k}}_{\perp,1}\right)\right] f_{\rm DY}^{\rm Sivers}(x_1, k_{\perp,1})\, f^{\rm unp}(x_2, k_{\perp,2})\, \delta^2\left(\vec{q}_\perp - \vec{k}_{\perp,1} - \vec{k}_{\perp,2}\right)$$

Example II: **SIDIS** $\mathbf{e\,p^{\uparrow} \to e\,\pi\,X}$



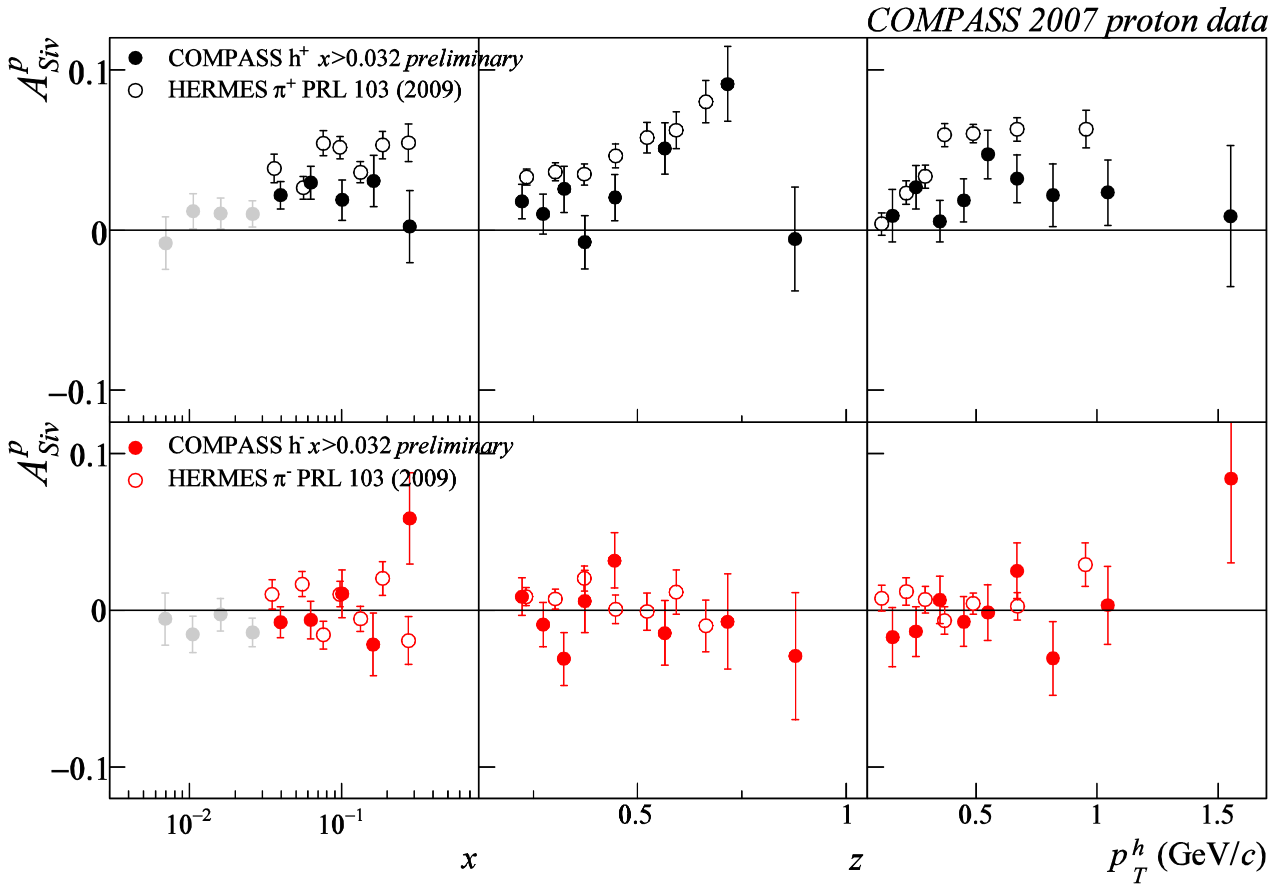
SMC, HERMES,
COMPASS, CLAS

$$A_N \propto \sin(\phi - \phi_S)$$

Sivers effect

$$\sum_f H(Q^2) \int d^2k_{\perp,1} \int d^2k_{\perp,2} \left[\vec{S}_\perp \cdot \left(\hat{\vec{P}} \times \hat{\vec{k}}_{\perp,1}\right)\right] f_{\rm DIS}^{\rm Sivers}(x_1, k_{\perp,1})\, D_f^{\pi}(z, k_{\perp,2})\, \delta^2\left(\vec{q}_\perp - \vec{k}_{\perp,1} - \vec{k}_{\perp,2}\right)$$

- **seen !**



- **phenomenology:**

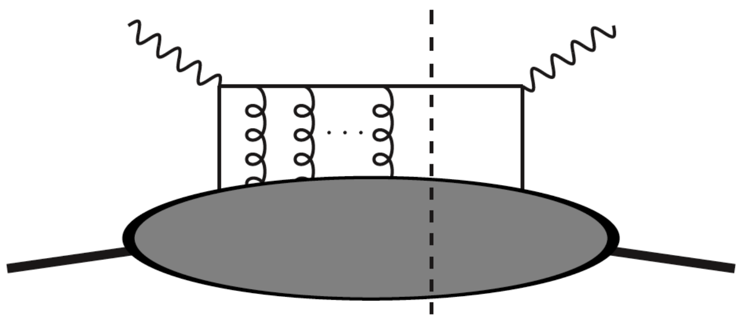
Goeke et al.; Anselmino et al.; Bacchetta et al.; WV, Yuan

Remarkably,

$$f_{\mathrm{DY}}^{\mathrm{Sivers}}(x, k_\perp) = - f_{\mathrm{DIS}}^{\mathrm{Sivers}}(x, k_\perp)$$ "non-universal"

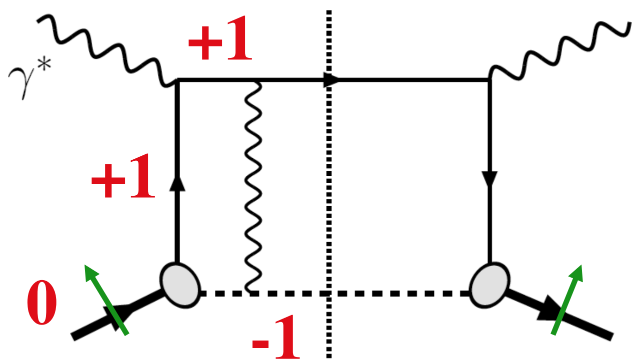
Brodsky, Hwang, Schmidt; Collins; Belitsky, Ji, Yuan; Boer, Mulders, Pijlman

- related to "gauge link" (rescattering) in pdfs:



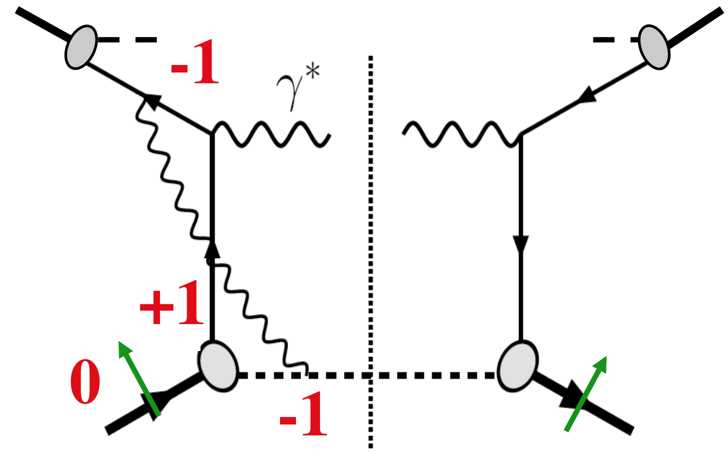
$$q(x) = \frac{1}{4\pi} \int dz^- e^{iz^- xP^+} \langle P | \bar{\psi}(0) \gamma^+ U_{[0,z^-]} \psi(0, z^-, \mathbf{0}_\perp) | P \rangle$$

$$U_{[0,z^-]} \equiv \mathcal{P} \exp\left(-ig \int_0^{z^-} d\xi^- A^+(\xi^-) \right)$$



DIS

"attractive"



Drell Yan

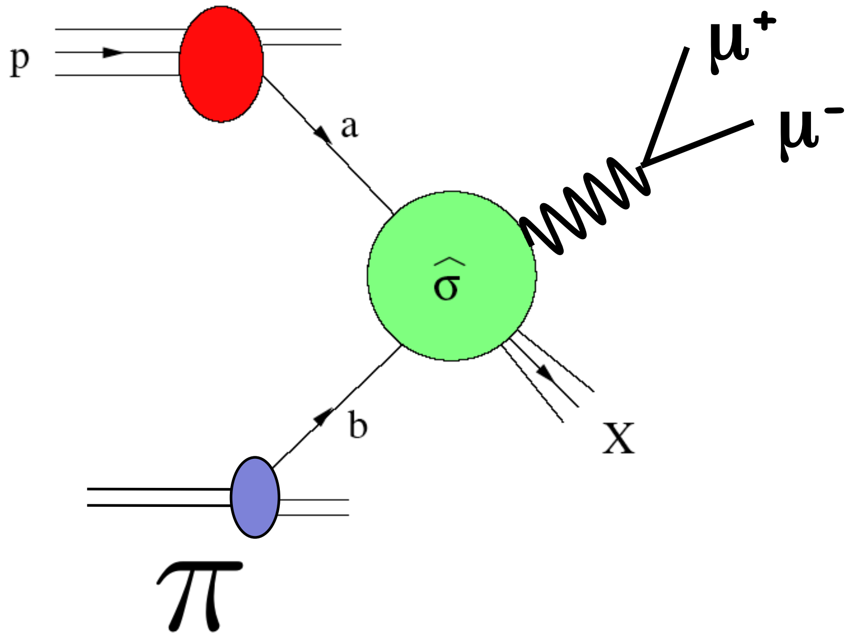
"repulsive"

- More complicated QCD hard processes:
  breakdown of "conventional" $k_\perp$ factorization beyond 1 loop
  Collins, Qiu; WV, Yuan, Rogers, Mulders
- Tests our concepts for description of hadronic processes
- Motivates COMPASS, RHIC,... Drell-Yan programs

Soft-gluon resummation and the valence structure of the pion

• Drell-Yan process has been main source of information on pion structure:

E615, NA10

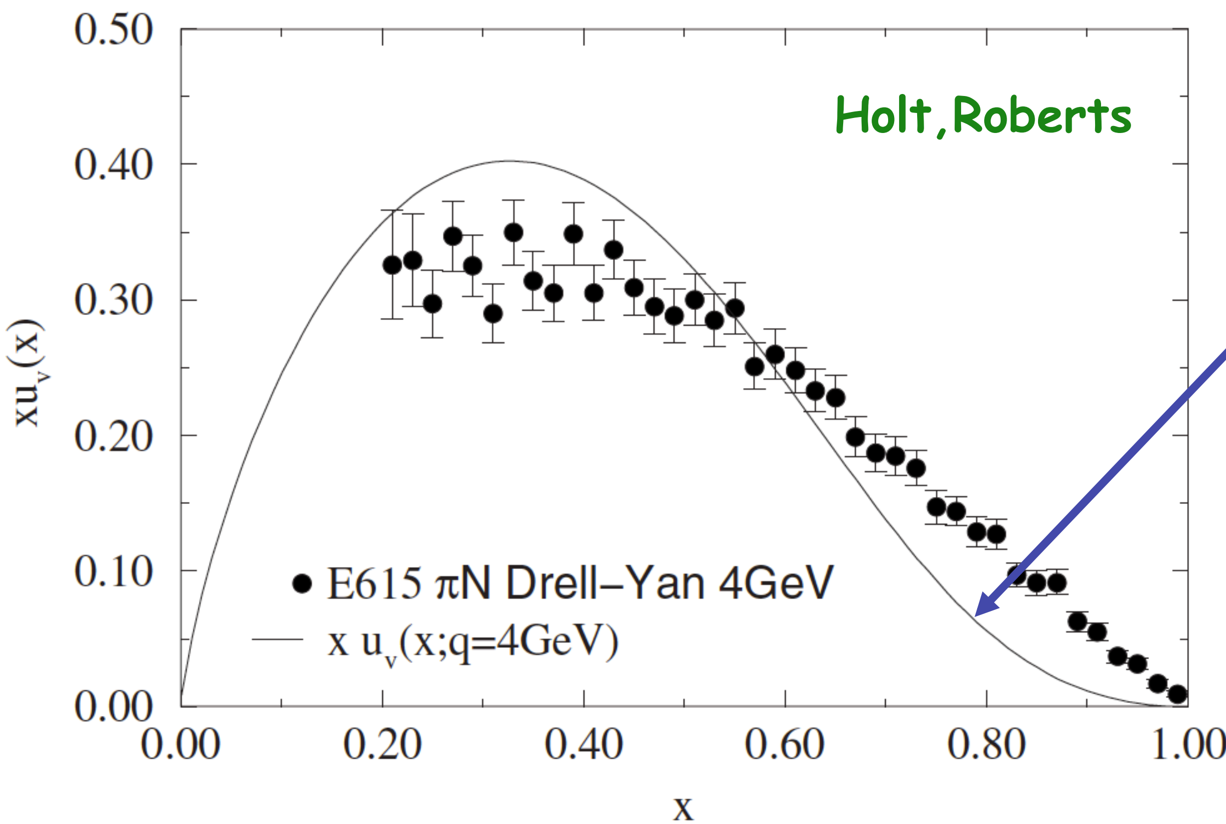


partonic hard scatt.
perturbative QCD

$$d\sigma = \sum_{ab} \int dx_a \int dx_b \, f_a^{\pi}(x_a, \mu) f_b(x_b, \mu) \, d\hat{\sigma}_{ab}(x_a P_a, x_b P_b, Q, \alpha_s(\mu), \mu)$$

• Kinematics such that data mostly probe valence region: ~200 GeV pion beam on fixed target

- LO extraction of u_v from E615 data:



$$\sim\ (1-x)^2$$

QCD counting rules

Farrar, Jackson; Berger, Brodsky; Yuan

Dyson-Schwinger

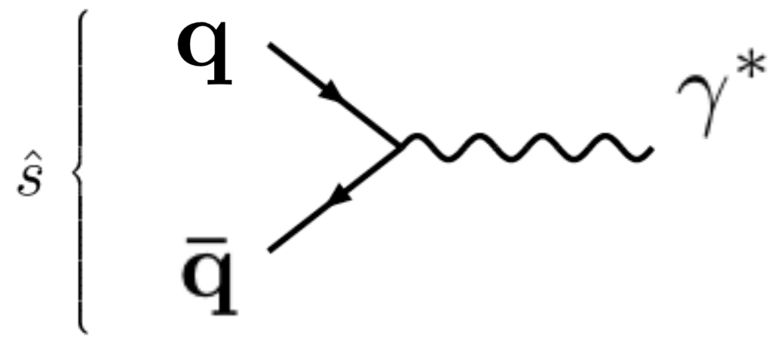
Hecht et al.

- other models can accommodate linear behavior

Shigetani et al.. Szczepaniak et al., Melnichouk

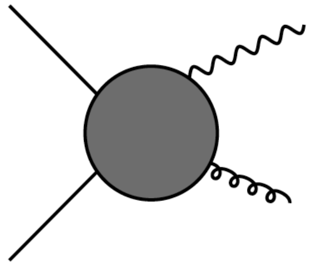
$$d\sigma = \sum_{ab} \int dx_a \int dx_b \, f_a^{\pi}(x_a,\mu) f_b(x_b,\mu) \, d\hat{\sigma}_{ab}(x_a P_a, x_b P_b, Q, \alpha_s(\mu), \mu)$$

LO :



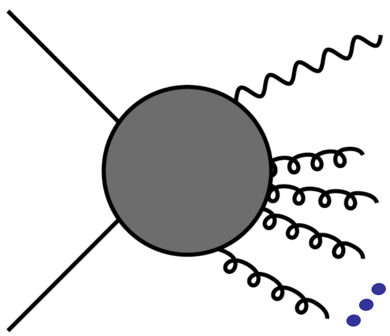
$$\hat{s} = Q^2 \quad , \text{ or } \quad z \equiv \frac{Q^2}{\hat{s}} = 1 \qquad \frac{d\hat{\sigma}^{(0)}_{q\bar{q}}}{dQ^2} \propto \delta(1-z)$$

- NLO correction:



$$\text{as} \quad \frac{Q^2}{\hat{s}} \equiv z \rightarrow 1 \qquad \frac{d\hat{\sigma}^{(1)}_{q\bar{q}}}{dQ^2} \propto \alpha_s \frac{\ln(1-z)}{1-z} + \ldots$$

- higher orders :



$$\frac{d\hat{\sigma}^{(k)}_{q\bar{q}}}{dQ^2} \propto \alpha_s^k \frac{\ln^{2k-1}(1-z)}{1-z} + \ldots$$

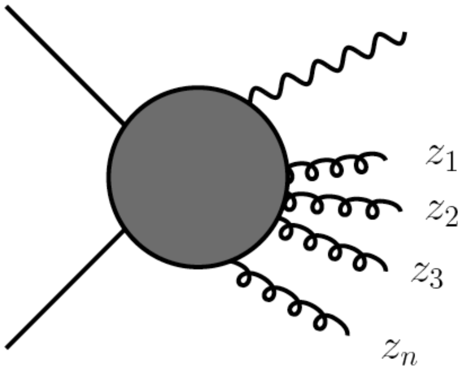
"threshold logarithms"

- particularly important in fixed-target regime

Large logs can be resummed to all orders

Sterman; Catani, Trentadue;...

- factorization of matrix elements
- and of phase space when integral transform is taken:



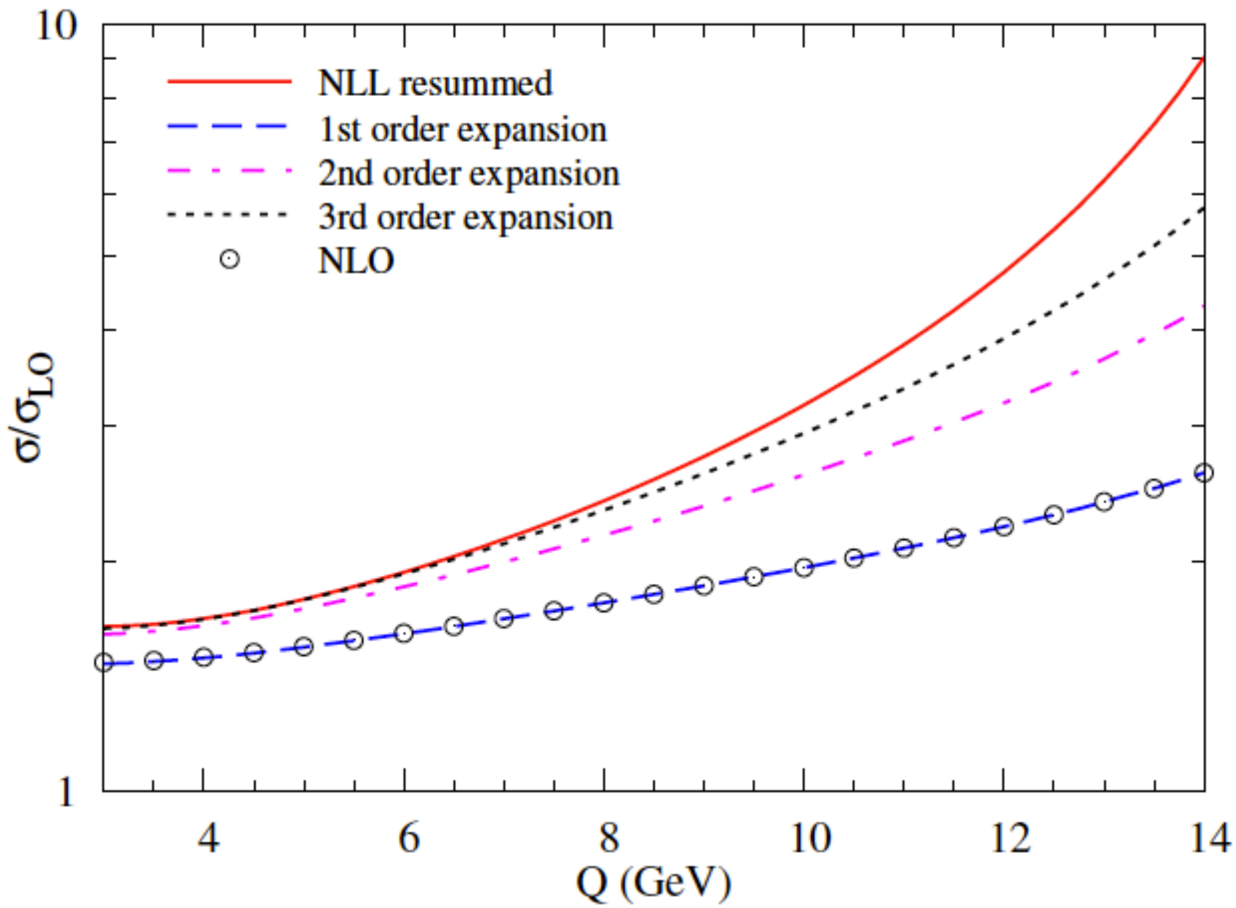
$$\delta\left(1 - z - \sum_{i=1}^{n} z_i\right) = \frac{1}{2\pi i}\int_C dN\, \mathrm{e}^{N\left(1-z-\sum_{i=1}^{n} z_i\right)}$$

$$z_i = \frac{2E_i}{\sqrt{\hat{s}}}$$

$$\hat{\sigma}_{q\bar{q}} \propto \exp\left[2\int_0^1 dy\, \frac{y^N - 1}{1-y} \int_{\mu_F^2}^{Q^2(1-y)^2} \frac{dk_\perp^2}{k_\perp^2} A_q\left(\alpha_s(k_\perp^2)\right) + \ldots \right]$$

$$A_q(\alpha_s) = C_F \left\{ \frac{\alpha_s}{\pi} + \left(\frac{\alpha_s}{\pi}\right)^2 \left[\frac{C_A}{2}\left(\frac{67}{18} - \zeta(2)\right) - \frac{5}{9} T_R n_f \right] \right\}$$

- they enhance cross section !

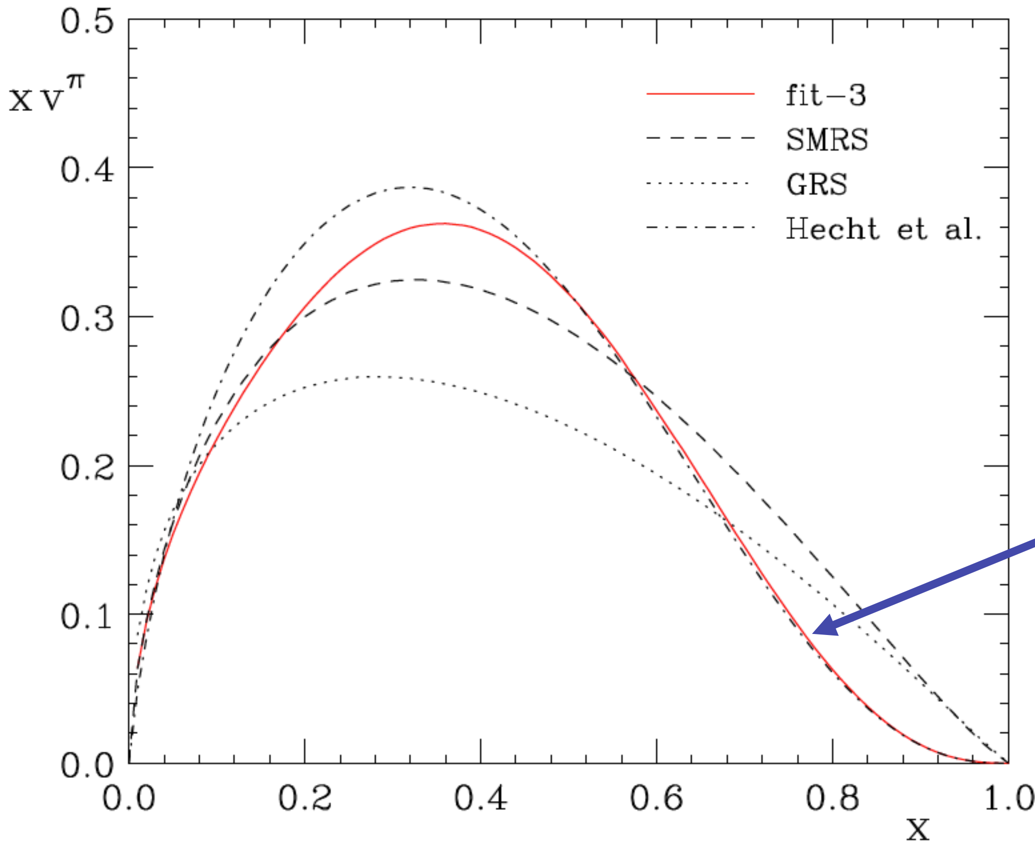


Aicher,Schäfer, WV

(Compass kinematics)

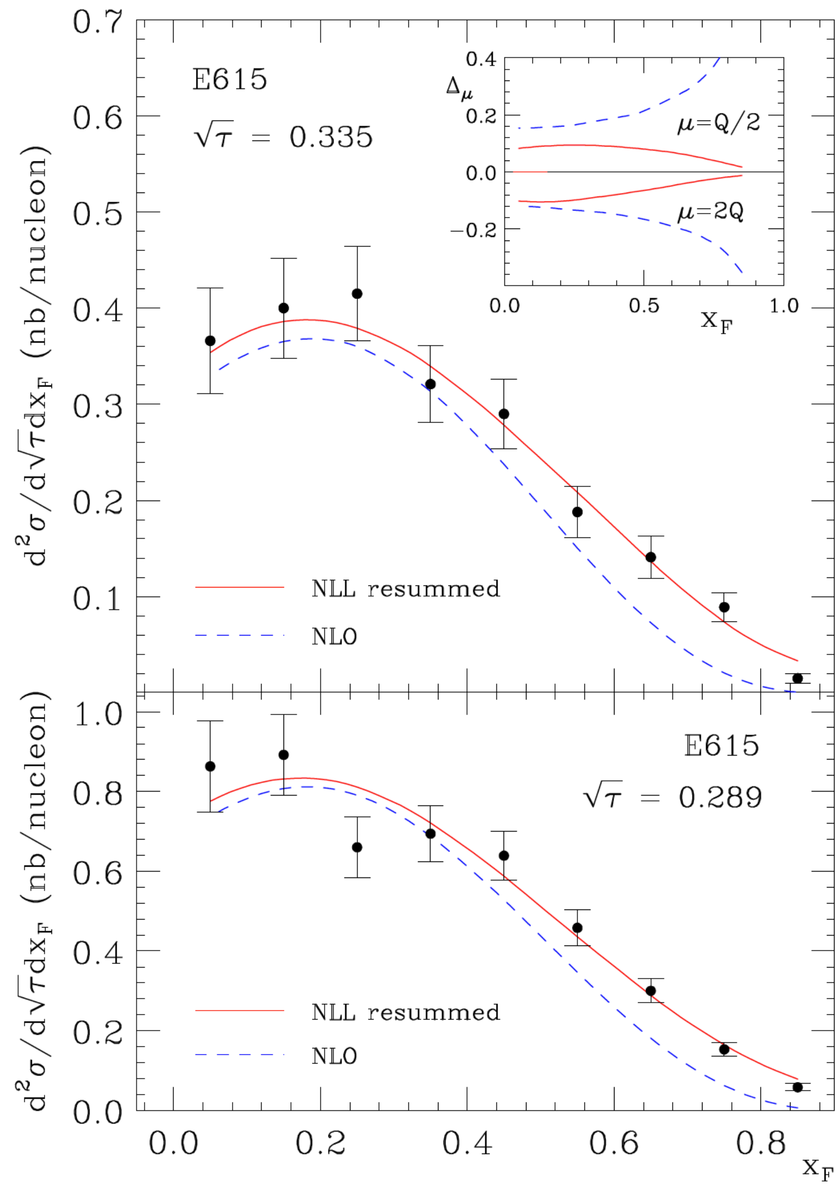
$$\sqrt{S} = 17\,\mathrm{GeV}$$

$$Q = 4 \text{ GeV}$$



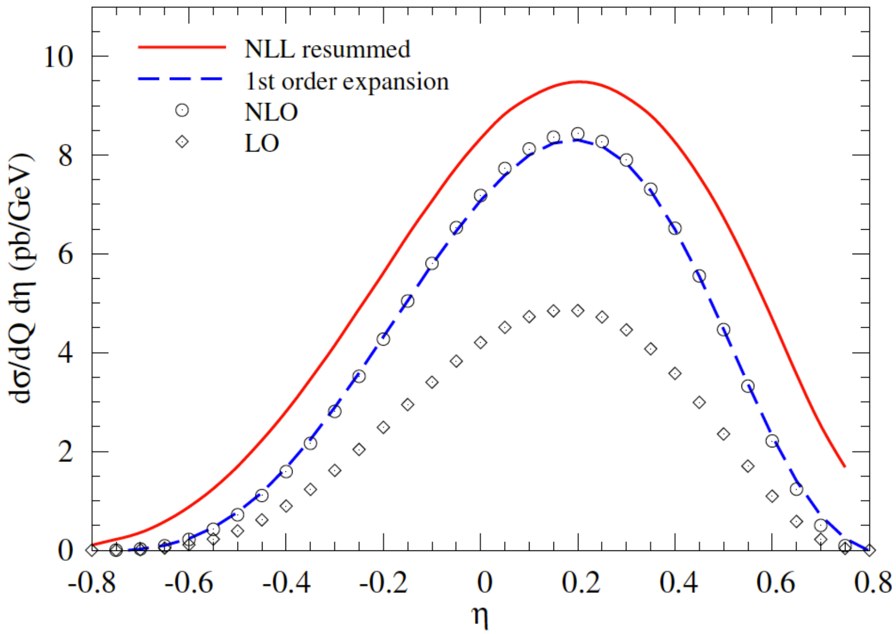
$$\sim\ (1-x)^{2.34}$$

Aicher, Schäfer, WV

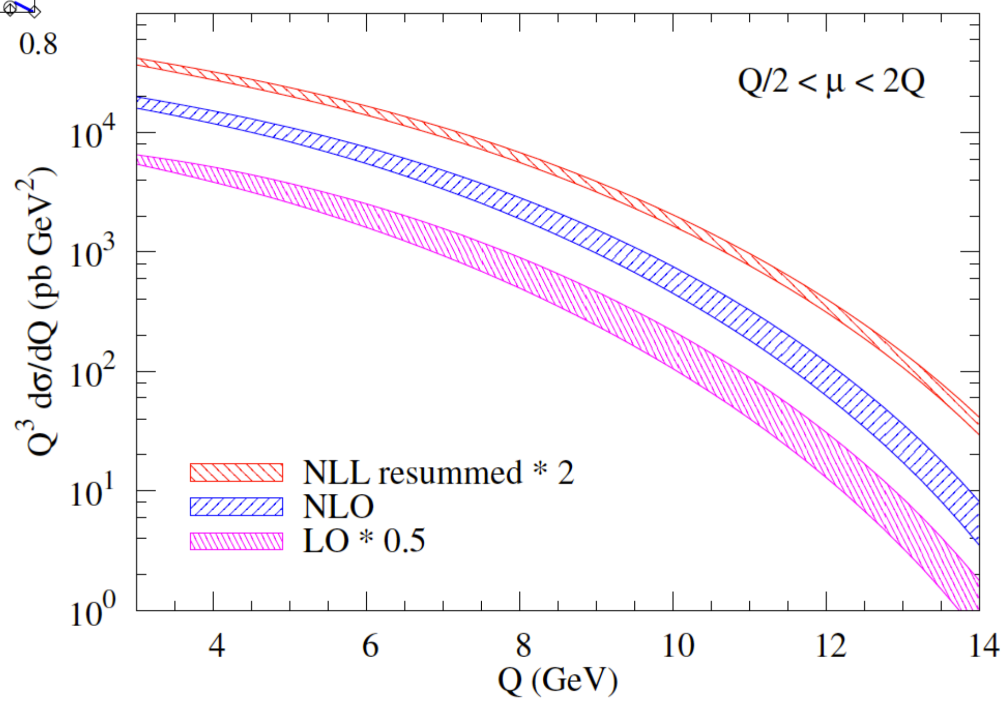


E615
$\sqrt{\tau}$ = 0.335
$d^2\sigma/d\sqrt{\tau}dx_F$ (nb/nucleon)
Δ_μ
μ=Q/2
μ=2Q
x_F
NLL resummed
NLO
E615
$\sqrt{\tau}$ = 0.289
$d^2\sigma/d\sqrt{\tau}dx_F$ (nb/nucleon)
NLL resummed
NLO
x_F

Equally relevant for COMPASS:

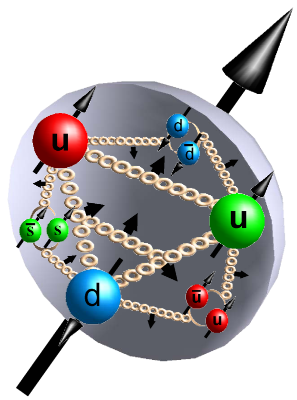


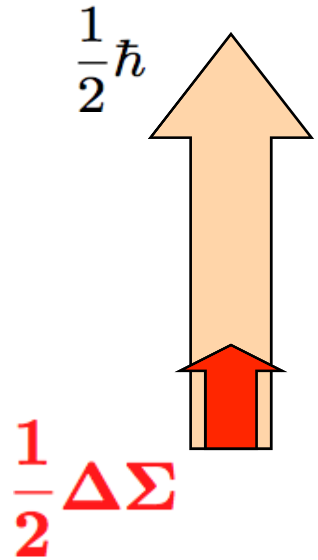
$$\frac{Q}{\sqrt{S}} = 0.45$$



Aicher, Schäfer, WV

Conclusions:





- RHIC & HERMES,COMPASS closing in on Δg:
  small in accessible x-region

- flavor asymmetry $\Delta\bar{u} - \Delta\bar{d} > 0$? Strangeness puzzle ?

- new insights into QCD from Drell-Yan

  - non-universality, pion structure, soft-gluon resummation effects